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Procedia CIRP 86 (2019) 239–244

www.elsevier.com/locate/procedia

7th CIRP Global Web Conference
"Towards shifted production value stream patterns through inference of data, models, and technology"

On The Change of Cost Risk and Uncertainty throughout the Life Cycle of Manufacturing Products

Oliver Schwabe[1, 2*], John A. Erkoyuncu[2] and Essam Shehab[2]

[1] Rolls Royce plc, UK
[2] Cranfield University, Building 50, Cranfield, Bedford MK43 0AL, UK

* Corresponding author. Tel.: +49-(0)-170-9053671. *E-mail address:* o.schwabe@cranfield.ac.uk.

Abstract

In practice cost estimators typically assume that cost risk and uncertainty continuously decrease across the whole product life cycle. Industry case studies and semi-structured interviews indicate that while cost risk and uncertainty decreases between technology readiness levels / stage gates, it increases when technology readiness levels / stage gates change. This increase can lead to cost risk and uncertainty levels above those at previous technology readiness levels / stage gates. This difference between assumptions in practice and evidence from case studies and semi-structured interviews may lead to the over- and / or under-assignment of capital reserves over time, thus resulting in binding project capital unnecessarily and / or the need to increase projects budgets in an unplanned manner. Further research is suggested regarding the scale of changes in cost risk and uncertainty when technology readiness level changes / stage gates are arrived at in order to improve robustness of forecasting efforts.

Keywords: Cost Risk and Uncertainty; Dynamic Propagation, Financial Contingency

1. Introduction

Increasing competition and regulation are raising the pressure on high value manufacturing organisations to innovate their products more and more rapidly [1]. Innovation is by default fraught by significant risk to and uncertainty of the accuracy of estimated unit and support costs [2,3,4]. This is not only due to the lack of historical data for orientation, but also due to fluctuations over time (time-dependency) [5,6]. The impact of these fluctuations may lead to the over- and / or under-assignment of capital reserves over time, thus resulting in binding project capital unnecessarily and / or the need to increase projects budgets in an unplanned manner [7].

Contemporary forecasting techniques thus do not always prove robust and it is hence not uncommon in practice for financial reserves to be held at higher programme levels to be flexed in the case of need. This involves the complex shifting of dynamic portfolio level reserves based primarily on tacit knowledge. To date these fluctuations have not been researched in detail primarily due to the inability to forecast cost risk and uncertainty (over time) without prior information [5]. The paper examines this time-dependent cost risk and uncertainty from ideation to production readiness for high value manufacturing products based upon the visualisation of uncertainty ranges over time which represent the paradigm applied in relevant forecasting [8,9].

Section 2 summarizes the concept of cost risk and uncertainty propagation based on a review of literature from industry and research. Section 3 shares the results of multiple quantitative and qualitative industry case studies, followed by a discussion of case studies in Section 4. Section 5 concludes the paper and provides recommendations for future research.

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10.1016/j.procir.2020.01.004

2. Literature review

The progression of cost risk and uncertainty can be considered analogous to the progression of cost estimate maturity / readiness levels [10]. Such levels are discussed in four key assessment frameworks starting with Bauman´s “flexible boundaries” in 1958 [11], revisited by the AACE International Recommended Best Practice 18R-97 “Cost Estimate Classification System” [12] in 1997, followed by Boehm´s COCOMO II “Uncertainty Funnel” in 1981 and 2000 [13,14], and then the NASA Cost Estimating Handbook “CRL Designation” in 2004 [10]. No such information was found in a number of wide spread industry standards such as put forward by NAVSEA [15], NATO [16,17], the UK Ministry of Defence [18], the US Air Force [19], or the US Naval Center for Cost Analysis [20], NASA [21,22,23], or the US Space Systems Cost Analysis Group [24]. Common to the key assessment frameworks identified is that they describe cost estimate accuracy ranges during the whole product lifecycle through boundaries of the shape of propagation as a result of (project) management actions.

Bauman´s work [11] is based on analysis of cost estimates for 10 chemical plants for three project stages; the first stage (Study) had a cost estimate range of -29% / +3%, the second stage (Scope) a range -11% / +12%, and the third state (Project Control) a range of -7% / +6%. The AACE International Recommended Best Practice 18R-97 [12] uses five estimate classes from Class 5 “Concept Screening” (-20% to -50% / +30% to +100%), Class 4 “Study or Feasibility” (-15% to -30% / +20% to +50%), Class 3 “Budget Authorization or Control” (-10% to -20% / +10% to +30%), Class 2 “Control or Bid/Tender” (-5% to -15% / +5% to +20%) and Class 1 “Check Estimate or Bid/Tender (-3% to -10% / +3% to +15%).

Boehm [13,14] discusses these ranges as part of the COCOMO model for software cost estimation later refines these with the concept of the “uncertainty funnel”. He suggests ranges from the perspective of “Estimate Variability” for the stages “Initial Concept” (-75% / +400%), “Approved Product Definition” (-50% / +200%), “Requirements Complete” (-33% / +150%), “User Interface Design Complete” (-20% / +125%), “Detailed Design Complete” (-10% / +110%), and “Software Complete” (+/- 0%). The NASA Cost Estimating Handbook [10] discusses cost readiness levels (CRL) aligned against technology readiness levels based on project complexity and adequacy of estimating methods. Cost estimate uncertainty ranges are then presented for CRL 4 “Cost fit for very preliminary engineering decisions and very preliminary budget use” at +/-45%, CRL 5 “Cost fit for preliminary engineering decisions and preliminary budget use” at +/- 35%, CRL 6 “Cost fit for PDR engineering decisions and standards. PDR budget use at +/- 25%”, CRL 7 “Cost fit for firm engineering decisions and firm budget commitments” at +/- 15%, and CRL 8 “Cost fit for very firm engineering decisions and very firm budget commitments” at +/-5 %.

For comparative purposes the researchers chose common structural denominators as represented by the three stage milestone structure “Study”, “Scope” and “Project” originating from Bauman [11]. Specifically (a) for the NASA Cost Estimating Handbook the CRLs 4, 6 and 8 were used, (b) for COCOMO II the phases Initial Concept, Requirements Complete, and Detailed Design were used, and (c) for AACE the Classes 5, 4 and 1 were used. Figure 1 illustrates the high / low boundaries of the four key assessment frameworks normalized across these three generic stages.

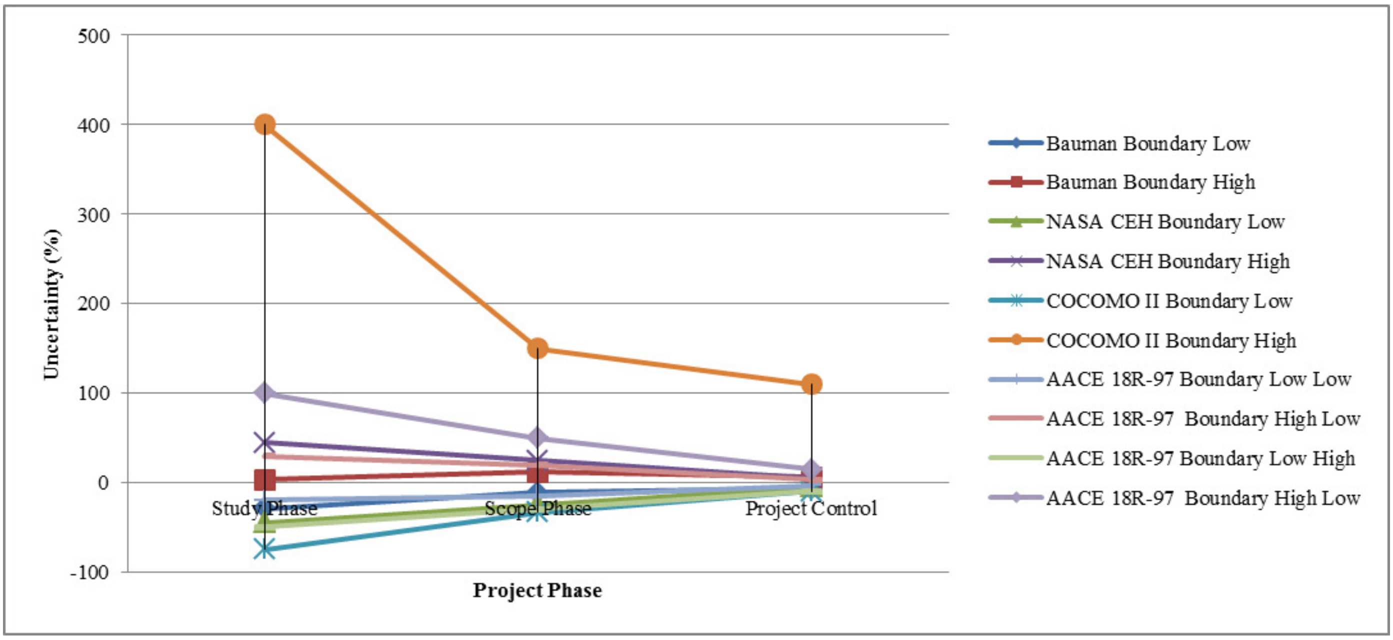

Fig. 1. Uncertainty progression for key frameworks

3. Industry case studies

The propagation behavior of cost uncertainty during the whole product life cycle is determined by the rise and retirement of risks and their associated probability distributions across this time period. Based upon a review of industry practice, three key approaches exist for evaluating this propagation: discrete numeric, discrete gross risk (DGR) and continuous DGR. DGR describes a range of generic probability-impact values from "1" for very low probability / very low impact to 29 for very high probability / very high impact based on custom scoring schemes. These three approaches are applied to a whole product life cycle view. This is typically managed through a stage gate process and each stage gate is defined by series of questions and intended to examine treatments of risk threats raised previously in hindsight, provide insight to new risk threats typically encountered when entering the next stage gate phase and provide foresight of generic and specific risk threats expected at and between future stage gates.

3.1 Industry case study – discrete numeric

In a chosen industry scenario the stage gates start with a reflection on innovation and opportunity selection (Gate 0.1), followed by Preliminary Concept Definition (Gates 1.1 - 1.2B), to then consider Full Concept Definition (Gates 2.1A and 2.1B), Product Realisation (Gates 3.1 – 3.6B), Production and In-Service Support (Gates 4.1 and 4.2), Continuing In-Service Support (Gate 5.1) and then end with End of Life Disposal (Gate 6.1). In the chosen industry scenario a total of 2143 questions are raised during the stage gates whereby a total of 499 are specifically related to cost. Each question can be considered to inherently represent a risk threat or risk opportunity and thus if the number of (cost) risks considered at each stage gate changes (and if each risk has an associated uncertainty range associated with it regarding impact) then cost risk uncertainty should also change over time. Important to note is that in the industry scenario the focus is primarily on risk threats and not risk opportunities. Hereby it is also important to consider that the duration for which risks remain valid may extend beyond the next stage gate.

At each stage gate it is also common to include a financial review which is intended to assure that any financial resources reserved for unplanned cost changes are adequate and adjusted as necessary. Adjustment of financial reserves can mean the provision of additional funds / release of reserves which are not needed to the organisation for other use.

Figure 2 illustrates an industry example of the discrete numeric approach which focuses on the total number of generic questions at each stage gate of a whole product life cycle management process. The total height of each column represents the total number of questions, whereby the light grey section represents those questions specifically related to cost risks. The three stage milestone structure "Study", "Scope" and "Project" was aligned to Gate 1.2B "Business Concept Review", Gate 2.1B "Programme Commitment Review", and Gate 3.6B "Realise Business Review" respectively.

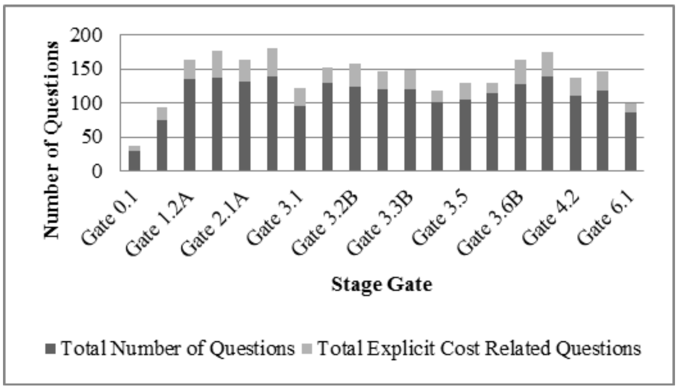

Fig.2. Industry case study – discrete numeric

3.2 Industry case study – discrete gross risk

The same data used for the discrete numeric approach was then examined using the DGR approach for a single aerospace component project for 10 exemplary risks as shown in Table 1. The numbers represent the DGR at the key three generic stage gates previously chosen based on Bauman []11:

Table 1. Industry case study – discrete gross risk

Risk ID	DGR Gate 1.2B ("Study")	DGR Gate 2.1B ("Scope")	DGR Gate 3.6B ("Project")
1	22	22	22
2	8	8	8
3	8		
4	27	27	27
5	5	5	5
6	18	18	
7	3	3	3
8	12	12	
9	12	12	12
10	22	22	22
SUM	137	129	99

The duration of the risks is given by the grey shading, i.e. risk ID 1 exists at gates 1.2B, 2.1B and 3.6B, while risk ID 3 exists only at gate 1.2B. At each gate the sum DGR is determined based on the sum of individual DGRs at that time. The individual risks may arise before or at the stage gate and retire at or after the stage gate. Over the duration of the risk a uniform probability distribution was applied due to the lack of further information.

3.3 Industry case study – continuous gross risk

While the discrete numeric approach counted the number of risks over the course of the whole product life cycle (see Figure 2), and the DGR approach counted the potential impact over time for the three generic stages, the DGR fluctuation between these can now be evaluated.as shown in Figure 3.

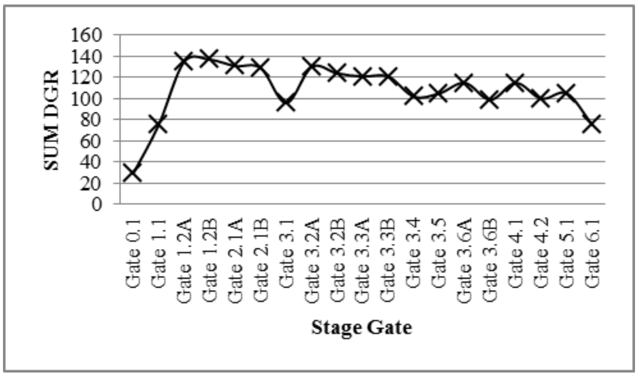

Fig. 3. Industry case study – continuous sum gross risk

The x-axis shows the progression over time whereby the three key generic stage gates 1.2B, 2.1B and 3.6B are highlighted by vertical dotted lines. While each risk probability number will have an uncertainty range associated with it, this can be disregarded for purposes of the initial evaluation, although a generic +/- range for each stage gate could be applied using one of the models discussed in the literature review. Examining the sum DGR at the stage gates it can be seen that at gate 1.2B it exceeds that of the previous gates and the sum DGR at gate 3.2A exceeds that from gate 2.1B. This could suggest that the uncertainty "cone" does not begin to come into effect before the project has achieved approximately gate 3.2A (approximately 1/3 of the way into the project). Examining the sum DGR behaviour between the gates it can be seen that it does not consistently drop between these as the uncertainty cone paradigm would suggest.

It is this behaviour which points to the challenge investigated by the paper. In these phases the sum DGR rises between stage gates and would, if they became issue, require more than expected and assigned contingency.

3.4 Semi-structured interviews

In order to explore the perceived progression of cost risk and uncertainty over the course of the whole product life cycle an online case study as designed as a survey and shared with the cost estimation communities of two major UK aerospace manufacturers in March 2019. Using a generic probability impact diagram, participants were asked to assess the risk threat and risk opportunity (on a scale of 1 (very low) to 29 (very high) for seven generic whole product life cycle stages (Stage 0: Opportunity Definition, Stage 1: Preliminary Concept (Demonstrator), Stage 2: Full Concept (Prototype), Stage 3: Product Realisation (First unit), Stage 4: Production and In-Service Support (Series production), Stage 5: Continuing In-Service (Maintenance only), and Stage 6: End of Life Disposal). A total of 25 qualified responses were received and the results shown in Figure 4. For both risk threat and risk opportunity the mean of the response values is shown in addition to the highest and lowest scores captured.

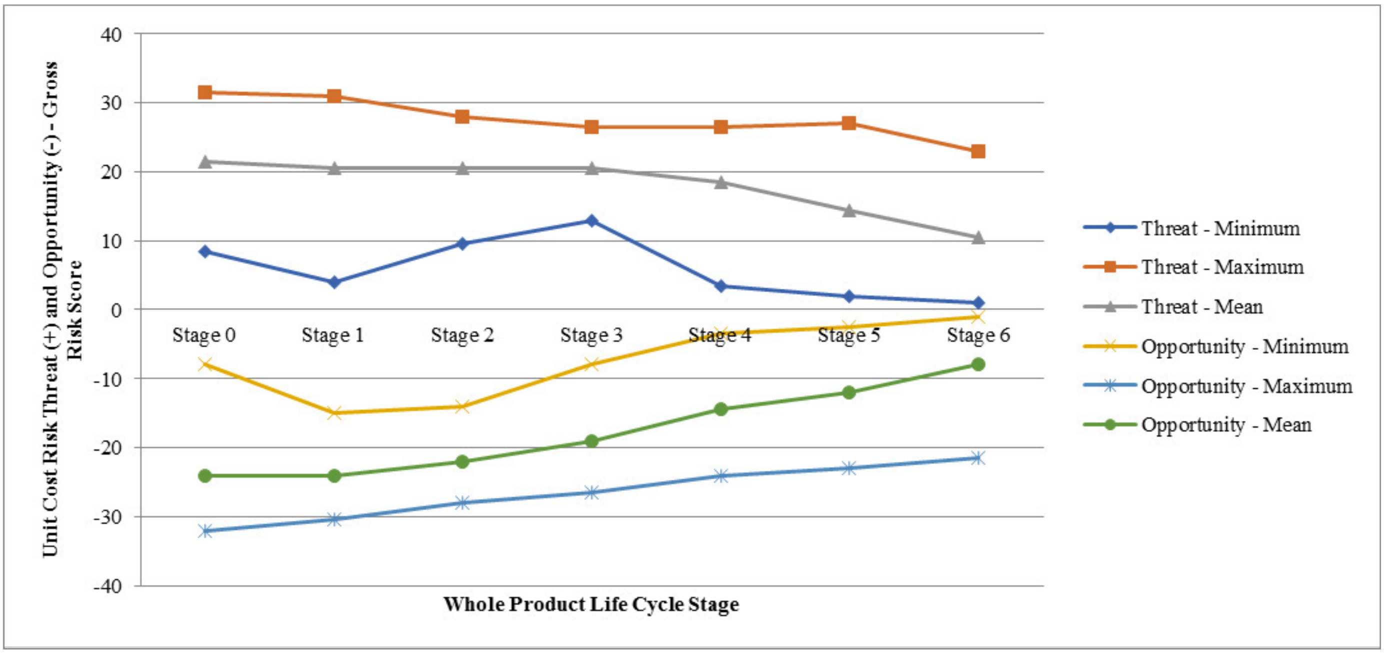

Fig. 4. Results of cost estimating subject matter expert community survey

4. Discussion

Based on the results of the literature review and case studies an attempt can be made to compare and contrast their differing perspectives. Additionally an Aerospace Industry Project Database case study created by an UK aerospace manufacturing company based on data from over 400 projects in 2017 and 2018 was added to the four key assessment frameworks and interview results. In this industry database the cost estimate readiness level (ERL) of projects as they evolved through the whole product life cycle stage gate process (see Figure 2) was assessed. Values from the ERLs 1, 5 and 9 were used to represent the generic three stage gated “Study”, “Scope” and “Project”. The comparative results are shown in Table 2.

Table 2. Uncertainty assessment framework boundaries

Uncertainty Assessment Framework	Study Phase (%)	Scope Phase (%)	Project Control (%)
Bauman Boundary Low	-29	-11	-7
Bauman Boundary High	3	12	6
NASA CEH Boundary Low	-45	-25	-5
NASA CEH Boundary High	45	25	5
COCOMO II Boundary Low	-75	-33	-10
COCOMO II Boundary High	400	150	110
AACE 18R-97 Boundary Low Low	-20	-15	-3
AACE 18R-97 Boundary High Low	30	20	3
AACE 18R-97 Boundary Low High	-50	-30	-10
AACE 18R-97 Boundary High Low	100	50	15
Semi-Structured Interviews Low (Mean)	-21	-16	-9
Semi-Structured Interviews High (Mean)	18	20	14
Aerospace Industry Project Database Low	-93	-44	-5
Aerospace Industry Project Database High	1,280	80	5

The high and low boundaries are then averaged as shown in Figure 5. The shape remains funnel-like and the risk opportunities remain significantly smaller than the risk threats. The imposed linear trend-lines suggest an iterative decrease of high / low boundaries which may obscure the dynamics between stage gates as shown in Figure 3.

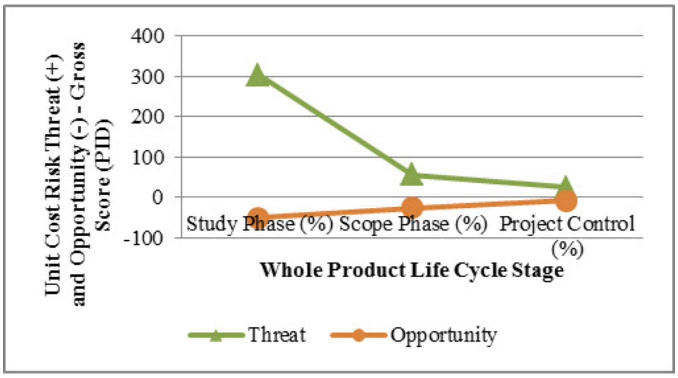

Fig. 5. Aggregated assessment frame boundaries

The assessment framework boundaries shown in Table 2 suggests that while all data sets provide discrete uncertainty range data for each of the three generic stage gates, it is the ensuing application of trend-lines on that data which anchors a perception of a continuous decrease in the value of high and low boundaries. The implicit suggestion is therefore that the value between the stage gate values the “cone” or “funnel” paradigm. This stands in contrast to Figure 3.

Of note is also that the application of trend-lines is a statistical method which by default requires a minimum amount of prior data which can be argued to be at least 41 data sets [25]. In the case of Baumann [11] only 10 data sets were used and a closer examination also indicates that the high boundary of the “Scope” phase is higher than the high boundary of the previous “Study” phase. Also of note is that in the NASA data [10] high and low boundaries always have the same absolute value which suggests that these may not be based on actual project data, while the AACE [12] boundaries for high and low also include a spread of these boundary values.

Any aggregated data and models derived from these will by default have degrees of uncertainty associated with them. Indeed this uncertainty is inherent in any measurement based approach and only the AACE model [12] points to this uncertainty for the boundaries themselves. It is especially the use of boundary trend lines in this respect which anchor expectations without emphasis of the fact that this propagation behavior is only due to project management interaction. Without this interaction the researchers suggest that the uncertainty related to a whole product life cycle would remain constant at best.

While the examples from literature and surveys suggest that the uncertainty cone paradigm can be applied a comparison against case studies suggest that this can only be considered an approximation under the assumption that management interventions properly address a continuously growing number of risk threats.

The stage gate process question analysis (see Figure 2) thus points to the growing nature of risk and uncertainty over time, the single product risk analysis (see Table 1) suggests that while between stage gates the sum gross risk and uncertainty will drop as a result of management intervention, it is at the next stage gate that the stage gate process injects a number of new risk threats whose sum gross risk may well exceed that of the previous stage gate.

In this respect the predictive capability of a paradigm such as the “uncertainty cone” can be considered as helpful for informing affordability discussion as suggested by Bankole et al. [26] or Erkoyuncu et al. [2] in relation to bidding stage decision making. This decision making support does however need to be tempered by the default anchoring of perceptions through the visualisation as a “funnel” shape as pointed out by Kreye at al. [27] which may suggest an illusion of predictability as highlighted among others by Ziliak [28]. Overall though it can be considered a helpful technique for supporting estimation without or with very little data similar to the creation of cost estimation models under such conditions as argued by Smart [29].

5. Conclusions and future work

The number of risks arising during the whole product life cycle increases continuously, whereby the overall number of risks relevant at and between stage gates fluctuates depending on various factors.

Sum gross risk may well decrease between stage gates, but will then increase by default on progression through the stage gate since new questions with relevant risk threats become relevant. The relationship between the sum gross risk values at stage gates will thus depend primarily on the degree that the risks raised at one stage gate have been mitigated before entering the next stage gate phase. Not only may a stage gate in itself introduce risk threats exceeding those of the previous stage gate in value, there may well be a "carry-over" of risk threats which have not been mitigated (or continue in relevance) since the risk expiration date may be later. In consequence the uncertainty ranges will fluctuate at / between stage gates.

In summary therefore cost risk and uncertainty propagate dynamically across the whole product life cycle and during this propagation it may increase to values and ranges greater than at previous points in time. This again suggests that the wide-spread paradigm of the "uncertainty cone" may represent primarily the intent of project management activities than anything else. This then supports the need for regular re-visitation of cost risk and uncertainty assessments and forecasts to ensure progression against the planned path of cost risk and uncertainty reduction. This difference between assumptions in practice and evidence from case studies and semi-structured interviews may lead to the over- and / or under-assignment of capital reserves over time, thus resulting in binding project capital unnecessarily and / or the need to increase projects budgets in an unplanned manner.

Further research is suggested regarding the scale of changes in cost risk and uncertainty when technology readiness level changes / stage gates are arrived at.

Acknowledgements

The authors would like to thank the members of the LinkedIn Group "Cost Risk and Uncertainty" for support in the interpretation and comparison of case study data.

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2020-02-18

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Schwabe, Oliver

Schwabe O, Erkoyuncu JA, Shehab E. (2019) On the change of cost risk and uncertainty throughout the life cycle of manufacturing products. Procedia CIRP, Volume 86, 2019, pp. 239-244
https://doi.org/10.1016/j.procir.2020.01.004